

## Considerations for an Exercise Prescription

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### Introduction

The development of an effective exercise prescription for long-duration space flight depends on the identification and understanding of various characteristics of the physiological response to muscular work in microgravity. We need to establish the optimum combination of intensity, duration, frequency, and mode of exercise that will be required to maintain normal cardiovascular reflexes, fluid-electrolyte balance, and musculoskeletal integrity for one-g as well as weightless environments. This determination will require accurate assessment of the normal prelaunch fitness levels of the astronauts and their specific work requirements for successful performance of operational activities and extravehicular activities (EVA's) during flight as well as those for safe return to Earth.

I should like to use this opportunity to present a number of our past and most recent research findings that describe some of the physiological responses to exercise in man and their relationship with exposure to various gravitational environments. Most of our data pertain to adaptations of the cardiovascular and body fluid systems. It should be kept in mind that our data from studies on microgravity simulation in man include exposures of relatively short duration (5 hours to 14 days). However, I believe that our results may provide important guidelines for the consideration of many variables which are pertinent to the development of exercise prescription for long-duration space flight.

### Fitness Requirements for Astronauts

M. A. Berry and associates (ref. 1) have reported that the average aerobic capacity ( $\text{VO}_2$  max) of U.S. astronauts is approximately 45 ml/kg/min. This level of aerobic fitness is average for individuals in the astronaut age group (35 to 50 years). There is little documentation of their strength fitness. However,

the available data from space-flight and ground-based studies suggest that performance of EVA, the most vigorous, muscular work performance in space, requires significantly greater muscular endurance than maximum contractile strength.

I will start by trying to provide some perspective on the energy requirement for work during EVA. Tom Moore has presented some relevant data on the absolute levels of energy exchange. Although these work levels may appear small based on metabolic measurements, it is important to address the point raised earlier by Reggie Edgerton regarding how much relative work is performed by the specific muscle groups involved during EVA. The mean oxygen uptake ( $\text{VO}_2$ ) over 3 to 6 hours of EVA during various Space Shuttle missions was approximately 0.8 liter/min. However, the  $\text{VO}_2$  required for peak work output of short duration (minutes) during nine EVA's (averaged over six missions) was about 1.6 liters/min. Our data from normal individuals and from wheelchair-dependent subjects (i.e., paraplegics and amputees) who use their arms routinely indicate that the  $\text{VO}_2$  max of the arms for individuals at similar aerobic fitness levels as the astronauts is approximately 1.8 liters/min (ref. 2). Since muscular work during EVA requires predominantly arm activity, astronauts are functioning for hours at an average exercise intensity of 45 percent  $\text{VO}_2$  max with short periods requiring as much as 80 percent of the maximal working capacity of the arm and upper body muscle groups. Based on these data, I suggest that astronauts train both before flight and in flight specifically to maintain high aerobic fitness and endurance of the arms as well as some degree of arm strength.

The requirements of muscle strength for EVA are poorly defined. Although the astronauts have reported fatigue following EVA, this condition may be more representative of poor endurance of arm muscle groups as well as related to strength characteristics. Since objects in space are theoretically "weightless," it appears unlikely that astronauts would require great

arm strength to lift and move objects. However, an accurate assessment of muscle strength requirements for working in space awaits measurements of muscle forces produced during specific work tasks.

### Concern for High Aerobic Fitness

Since muscular endurance as well as strength seems to be required for successful performance of EVA, the relationship between preflight aerobic fitness level of astronauts and orthostatic intolerance is an important issue that should be addressed. Historically, this issue has become very controversial and should be considered when developing exercise prescriptions for astronauts.

Last week, Don Stewart asked me to prescribe an exercise program for long-duration space flight based on my current knowledge. I emphasized that the beginning fitness level will determine the exercise prescription for space flight. Data from our bed-rest studies indicate that the reduction in work capacity and cardiovascular responsiveness to orthostasis following simulated weightlessness is twice as great in highly fit individuals compared to unfit individuals (refs. 3 to 5). From these and other data, it has been suggested by numerous investigators that unfit individuals should be chosen for space flight. This suggestion does not seem practical based on the endurance requirements for EVA presented earlier. Furthermore, despite greater loss, the  $\text{VO}_2$  max and working capacity of trained subjects remains significantly higher than that of untrained subjects following simulated weightlessness (refs. 3 to 5). For this reason, I suggest that we select astronauts for EVA who have high endurance and strength in the arm and upper body musculature. Based on some of our results (ref. 6), I propose that the greater, more rapid reduction in functional "reserve" in athletic subjects exposed to microgravity should not be considered physiologically adverse, but may indicate that these subjects adapt more readily to the weightless environment. However, the tendency for athletes to adapt (decondition) more rapidly in microgravity may indicate that the maintenance of physical work capacity in fit individuals will probably require a greater amount of exercise or other measures during space flight to maintain preflight fitness level. This should be an important operational consideration.

Another potential problem that has been raised is that high aerobic fitness in some studies has been associated with orthostatic intolerance. Furthermore, individuals who are more fit have a greater reduction in orthostatic tolerance than do

unfit subjects following simulated weightlessness. These data have been used to suggest that we should not select fit individuals as astronauts.

In an earlier presentation, Mary Anne Frey outlined the results of a number of our most recent studies. We have conducted a number of cross-sectional studies which were designed to examine the relationship among aerobic fitness, strength profiles, and orthostatic tolerance. One of these studies was performed on men and women before and after simulated weightlessness using a head-down bed-rest model (ref. 7). The aerobic fitness of our subjects has ranged between 30 and 70 ml/kg/min, a fitness range well within that of the astronauts. With this series of studies, we have observed no significant relationship among aerobic fitness, leg muscle strength, and orthostatic intolerance (refs. 8 to 10). Therefore, based on our data, I strongly suggest that an individual with moderately high aerobic capacity should be selected for the astronaut corps without concern for predisposition to orthostatic intolerance before or after space flight.

Finally, Gunnar Blomqvist asked if it has been established that aerobic training per se can reduce orthostatic tolerance. From nine longitudinal studies currently reported in the literature, there are no data that demonstrate a reduction in orthostatic tolerance following aerobic exercise training and increased  $\text{VO}_2$  max. Of these nine studies, four of them have shown no change and five of them have shown an increase in orthostatic tolerance (ref. 10). In terms of selecting a mode of exercise for prescription during space flight, it is rather interesting that a definite trend has developed: the four studies that showed no change in orthostatic tolerance all used running as the mode of training; four of the five studies that showed an increase in orthostatic tolerance used cycling. Further, increased orthostatic tolerance following exercise training was associated with increased plasma and blood volume (refs. 10 and 11). Therefore, endurance exercise training can be used to increase aerobic capacity and orthostatic tolerance when the mode of training produces a localized resistive component and hypervolemia (refs. 10 and 11).

### Preflight Training

Another important factor to consider for the development of exercise prescriptions for long-duration space flight is the preflight training. Most of us appreciate the concept of specificity of training. For example, the South African miners become most successful in their jobs because they have become

acclimatized to working in hot, humid environments. Our experience during operational tasks and EVA in space has demonstrated a predominant use of arms and upper body muscles for working and the use of legs for stabilizing the body. It seems that the most effective way to prepare an astronaut for specific requirements of working in space would include a preflight exercise training program which could be performed in a microgravity environment and is specific to increasing the strength and endurance of the arms. Therefore, swimming might be an excellent mode of training for preflight conditioning.

I did not have an appreciation for the potential use of swimming as a mode of preflight training until we completed a study more than a year ago that was conceived by one of my graduate students when I was a faculty member at the University of Arizona. The student was a former competitive swimmer. We were discussing possible thesis projects and he expressed a special interest in aerospace physiology. He made the anecdotal observation that when he was a competitive swimmer, he remembered that during the first week of returning for training for his competition, he was forced to get out of the water frequently to go to the bathroom to urinate. After the first week of training, he recalled that he could stay in the water for the duration of the training session and had no symptoms of diuresis, suggesting that there was an adaptation to exercising in a microgravity environment.

Since I have been interested in examining the mechanisms associated with the diuresis and natriuresis of weightlessness, we decided to perform an immersion study (ref. 6). We compared various renal and hormonal responses during 5 hours of water immersion to the neck in three groups of subjects: a sedentary control group, a group of competitive long-distance runners from the university track team, and a group of swimmers from the university swimming team matched for aerobic fitness with the runners. We also examined alterations in responses of heart rate and blood pressure during a 10-minute cycle exercise at 35 percent of  $\text{VO}_2$  max before and after immersion as an index of how the cardiovascular response may have been altered by 5 hours of water immersion. We found that the control group and the runners did show a change that indicated greater cardiovascular stress - they increased their resting and exercise heart rate by 10 bpm, and a number of the subjects had unstable blood pressure indicating some problems with orthostasis. The swimmers showed no change whatsoever in any of their cardiovascular responses, suggesting that training in a microgravity environment might provide some specific protective

effect against cardiovascular deconditioning during exposure to weightlessness.

Therefore, one factor we should consider in the development of an exercise prescription for long-duration space flight is to make available to the astronaut corps various preflight training programs that can be performed in water. Specifically, swimming may represent the most effective preflight training mode since it is performed in a buoyant (microgravity) environment, emphasizes training of the arms while the legs are used primarily for stabilizing the body, and appears to provide some protective effect against the cardiovascular deconditioning effects of weightlessness.

### In-Flight Training

The assessment of an appropriate in-flight exercise prescription should be centered around the objectives for maintaining in-flight and postflight task performance. One might contend that arm exercise during space flight should be emphasized because of the predominance of the muscle activity of the arms and upper body compared to that of the legs. However, our data and the review of other studies suggest that the functional capacity of the arms is minimally reduced following long-duration simulated weightlessness and that low-intensity exercise can maintain arm strength (ref. 12). This effect may be due to the use of cycle ergometers and the arm exercise associated with stabilizing the upper body. Therefore, appropriate preflight training and normal in-flight activity may be adequate for maintaining the working capacity of arm muscles during long-duration flight.

Leg exercise will be required during long-duration flight to protect astronauts during and after return to the one-g environment, when they will require the muscular and skeletal, as well as cardiovascular, integrity to safely and effectively resume the standing upright posture. Exercise of the leg muscles during space flight is probably most critical since these muscle groups are more likely to lose their functional capacity compared to the arms and upper body (ref. 12). U. C. Luft and coworkers (Lovelace Foundation) demonstrated that high leg (venous) compliance and blood pooling were associated with orthostatic intolerance. In a recent study (ref. 13), we measured leg compliance in 10 men and correlated these measurements with various functional and anthropometric characteristics of muscle associated with fitness. We included measurements of leg cross-sectional area of muscle

determined by computer tomography scan. We performed a multivariate regression analysis to explain the variation in the measurement of leg compliance. The only factor that significantly contributed to the prediction of leg compliance was muscle mass; i.e., the cross-sectional area of the muscle in the leg independent of the individual's muscle strength or aerobic fitness level. Thus, from a cardiovascular standpoint, there can be an argument for maintaining the integrity of the leg muscle mass during space flight.

In regard to the question of the need for in-flight exercise raised by Mike Bungo, I will reemphasize my "yes" response. Through our experience with long-duration simulated weightlessness (bed rest) studies, we have certainly verified that there are physiological problems in maintaining work capacity and normal orthostatic function following weightlessness. We have further evidence that exercise can ameliorate these problems to some degree. I think the more important question is "How much exercise is required during space flight?" We now have evidence that protection of the cardiovascular reflex responses following long-duration exposure to microgravity may only require one maximal aerobic exercise regimen once every 10 days. In one study (ref. 14), I tested 10 subjects with supine cycle ergometry followed by an upright treadmill test (similar to the test given to the astronaut corps) before and after 10 days in the 6° head-down position (simulated microgravity). The subjects performed maximal exercise during both treadmill and cycle tests. Before the subjects got up from bed rest, they repeated the supine cycle test, and we found a decrease in working capacity of 8 percent, which is very consistent with our previous finding (refs. 3, 5, 6, 15, and 16). Following the supine test, the subjects were allowed to ambulate and drink water ad libitum for 2 hours followed by their maximal treadmill test. Bengt Saltin and coworkers (1968) reported the largest reduction in  $\text{VO}_2$  max (26 percent) following bed rest when an upright treadmill test was used. Their subjects probably experienced some adverse orthostatic effects. Based on Saltin's observations, we hypothesized that there should be a greater reduction in  $\text{VO}_2$  max during treadmill compared to the cycle test. However, there were no reductions in  $\text{VO}_2$  max and no change in blood pressure or heart rate responses before, during, or after the exercise test in the upright position. Our apparent restoration of physiologic response following one bout of maximal exercise was similar to that of John Holloszy and coworkers (Washington University), who reported that one bout of maximal

exercise restored insulin receptor sensitivity, which was significantly reduced following 10 days of deconditioning in competitive long-distance runners. Similarly, Howie Green (University of Toronto) demonstrated that the increase in plasma volume with training could occur in 3 days, the same 12-percent increase we observed after 8 days (ref. 17). The major difference in training regimen was that they used maximal exercise and we used 65-percent  $\text{VO}_2$  max. Based on these data, I propose that one bout of maximal exercise performed 7 to 10 days in flight may provide an optimal stimulus to restore or maintain normal responses of cardiovascular function as well as some metabolic and fluid-electrolyte systems at preflight levels. From an operational standpoint, this proposal has important implications with regard to minimizing the amount of exercise time that might be required to protect the cardiovascular and fluid-electrolyte systems, and could also become a basis for more emphasis being placed on the development of specific exercise prescriptions to protect against deterioration of muscle and bone.

Boening and Stegemann (West Germany) compared orthostatic responses in trained and untrained subjects before and after 6 to 8 hours of water immersion. They proposed that trained individuals are less suited for space flight since they tended to faint following immersion, whereas the untrained subjects did not have a significant orthostatic problem. When the trained subjects repeated water immersion a second time, but performed maximal swimming exercise 1 hour before they got out of the tank, syncopal episodes were eliminated. These data reinforce my hypothesis that maximal stimulation of cardiovascular and fluid control systems by high-intensity exercise is adequate in reversing fluid-electrolyte and cardiovascular alterations associated with exposure to microgravity.

### Postflight Training

Although physiological limitations to muscular work and orthostasis immediately after reentry are a concern, it is also necessary to consider the effects of a long-term recovery rate as a factor limiting the resumption of normal physical activity following flight as well as the return to subsequent missions. The bed-rest study of Saltin and coworkers (1968) is often cited as evidence favoring the use of exercise conditioning programs as an effective technique for enhancing the recovery from the deleterious effect of microgravity on exercise performance. We found that reductions in  $\text{VO}_2$  max and exercise capacity following 14 days of

bed rest were returned to pre-bed-rest levels after 3 weeks of recovery using 30 minutes of daily exercise at 50-percent  $\text{VO}_2$  max (ref. 18). Furthermore, this complete recovery of functional work capacity was similar following repeated exposures to bed rest (ref. 18).

However, in a study of 12 middle-aged men (45 to 55 years) who had been at bed rest for 10 days (ref. 19), we randomly assigned six subjects to perform individually prescribed physical exercise daily for 60 days after bed rest (exercise group), and six simply resumed their customary activities (control group). Despite a significantly greater increase in  $\text{VO}_2$  max in the exercise group at 60 days compared to the control group,  $\text{VO}_2$  max and physical work capacity in both groups returned to pre-bed-rest levels by 30 days after bed rest. We concluded that simple resumption of usual physical activities after bed rest was as effective as formal exercise conditioning in restoring the functional capacity. These results are further supported by our more recent data demonstrating that pre-bed-rest  $\text{VO}_2$  max values were restored by 14 days of recovery from repeated 10-day bed-rest periods in nine healthy middle-aged men (35 to 50 years) who merely resumed normal daily activities with no daily exercise (ref. 3).

Therefore, recovery from exposure to weightlessness can be supplemented with a formal exercise prescription if desired. However, with regard to exercise metabolism and functional work capacity and endurance, 2 weeks of minimal daily activity are adequate for complete recovery from the deconditioning effects of microgravity, and repeated missions should be safely tolerated.

### Summary

We have a formidable task in determining the optimum exercise prescription for long-duration space flight. From an operational standpoint, we need to consider a program which will minimize the time required on an exercise device, yet will enhance Space Station crews to work most effectively in space and be returned to Earth in a healthy, functional condition, as close as possible to that which they enjoyed prior to their mission. With regard to cabin space, we need to consider the least amount of and smallest exercise equipment which will facilitate aerobic and cardiopulmonary conditioning and provide maintenance of full body strength and size of muscles and bones as well as protect against the adverse effects of alterations in body fluids and cardiovascular function.

I have presented the results from several of our experiments which have allowed us an opportunity to examine the interrelationships among exercise training, physical fitness, functional working capacity, and orthostatic intolerance before and after simulated weightlessness in man. Although our observations are limited to exposure in microgravity for relatively short duration, I propose that our data can be used for formulating the following considerations for exercise prescriptions during long-duration space flight.

1. Relatively high aerobic fitness and strength, especially of the upper body musculature, should be a criterion for selection of astronauts who will be involved in EVA, since endurance and strength appear to be predominant characteristics for work performance.

2. Some degree of upper body strength will probably be required for effective performance of EVA. However, the endurance and strength required by the upper body for EVA can probably be obtained through preflight exercise prescription which involves swimming. In addition, preflight swim training is attractive since it may provide protection against some of the cardiovascular deconditioning induced by weightlessness.

3. Although some degree of arm exercise may be required to maintain preflight endurance and strength, I propose that regular EVA will probably be sufficient to maintain the endurance and strength required to effectively perform work tasks during space flight. An emphasis for in-flight exercise should be placed on the use of the larger leg musculature. Specifically, cycle ergometry may represent one of the most effective modes of training since it can provide aerobic and resistive components for maintenance of muscle endurance and strength.

4. A minimum of one maximal aerobic exercise every 7 to 10 days during space flight may be all that is necessary for maintenance of normal cardiovascular responsiveness and replacement of body fluids for reentry following prolonged space flight. Therefore, a smaller portion of the exercise prescription in flight may be required for these systems and a larger portion can be committed to maintaining the integrity of muscle and bone.

5. At the NASA John F. Kennedy Space Center, we are currently studying the efficacy of electromyostimulation (EMS) as a potential countermeasure against muscle atrophy effects of microgravity. The possible reduction in the amount of exercise required for maintenance of cardiovascular system and body fluids in combination with the use of EMS or methods other than conventional exercise for

maintaining size and strength of muscles and bones needs great consideration for further research. These approaches represent a potential solution to the problem of compromising valuable time for exercise that is needed for daily operations.

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